Discerning mineral association in the near infrared region for ore sorting

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Abstract

The preconcentration or early rejection of gangue minerals in mineral processing operations is investigated using sorting, based on interpretation of near infrared sensor data collected from ore particles. The success of sorting depends on the distribution of minerals between particles, the arrangement or association of minerals within particles and the ability of near infrared to distinguish relevant minerals. This paper considers minerals association, using common alteration minerals found in a hydrothermally-formed copper ore, with sensitivity in the near infrared region. The selected NIR-active minerals were arranged along the view of NIR line scanner to stimulate adjacent natural minerals association.

It was found that spectral dominance may depend on minerals near infrared sensitivity and or the position of a mineral along the NIR scanner line of view. Analysis also revealed that only free occurring waste mineral spectra can be targeted for discrimination. Where spectra appeared mixed, such material cannot be preconcentrated using near infrared sensors.

Keywords: Near infrared line scanner, preconcentration, copper, gangue, association.

1. Introduction

The early rejection of gangue minerals, by automated sensor-based sorting of coarse ore particles has been shown to be a viable option to many mineral processing application[1,2,3,4]. A technique which shows promise for enabling preconcentration is Near InfraRed (NIR) spectroscopy[2],[4] to measure the use of measured reflectance of constituent minerals[4,5,6]. Understanding the mineralogy and characteristic NIR spectra signature of minerals in the ore is central to developing a successful strategy for implementation of a NIR sensor-based sorting application to minerals preconcentration[2,4,5,7].

NIR sensing consists of measurement of the reflectance of particle surface areas illuminated with NIR light and interpreting this information in terms of mineralogical information[7]. The aptness of the use of NIR point and line scanners as a means of acquiring information on the mineralogy of an ore has been reported[7]. While the point scanner measures a single spectrum

of a small surface area of the particle surface, the line scanner measures NIR spectra on a succession of adjacent areas across the mineral surface. Hence, a line scanner could provide the required data flow to drive improvement in ore control and processing, leading to reduced processing cost and higher yields in mining operations. Characterisation of the mineralogical composition of ores of heterogeneous nature using NIR scanners can be somewhat challenging depending on the complexity of the minerals association within the ore[5]. To prove the concept of NIR sensor-based sorting for a typical hydrothermally-formed copper ore[8,9], selected NIR-active minerals were arranged to simulate adjacent natural minerals association and NIR spectra were generated by a line scanner

2. Material and methods

Samples of pure calcite, muscovite, hematite, chrysocolla, and malachite were analysed with X-Ray Diffraction (XRD, Siemens/Bruker D5000, www.bruker.com). XRD measurements were matched with known minerals marker using Bruker EVA software. Results of XRD indicated that the samples were of high purity.

The NIR spectra were measured using a line scanner, which acquires spectral data at a pixel size of 2.9 by 9 mm. Details on the NIR background, procedure of data acquisition, instrumentation and data pre-treatment are described in Iyakwari et al. (2013) and Iyakwari and Glass (2015).

Measured adjacent particle areas (pixels) which were aligned either ‘parallel’ or ‘perpendicular’ to the direction of belt motion were prepared and investigated. The prepared particles were positioned for scanning in such a way that individual minerals in the field of view of the scanner were optically separated. All minerals had an average thickness of 0.7 cm.

For the perpendicular alignment, analysis involved the use of both solid and powdered samples (Figures 1 and 2). Solid mineral samples were cut into size and shaped to fit in close contact with one another. Powdered samples were obtained by crushing individual mineral samples using a Retsch steel jaw crusher (to -3 mm), then milled to -45 µm using a tungsten-carbide mill. The powdered samples were carefully poured into a 3.3 cm container demarcated into 1.1 cm each, in such a way that they made contact with each other at their boundaries. The powdered samples consisted of calcite-hematite-muscovite, arranged side-by-side (Figure 4), while the solid samples consisted of two minerals per analysis (Figure 2). The solid samples analysed included: hematite-chrysocolla (Figure 5), malachite-hematite (Figure 6) and calcite-malachite (Figure 7).

To investigate the influence of parallel minerals alignment when scanned by NIR line scanner, where minerals appear in contact side-by-side with parallel adjacent alignment to the motion of the NIR belt, only solid samples were prepared (Figures 3a and 3b) and scanned. Given a spectrum height of 0.9 cm, each mineral was cut to fit into half the spectrum height (i.e. 0.45 cm). Analysis consisted of two minerals per scan. Individual minerals were arranged side-by-side and then scanned with their position switched (transposed). Mixtures analysed included: hematite and chrysocolla (Figures 8a and 8b), malachite and hematite (Figures 9a and 9b) and calcite and chrysocolla (Figures 10a and 10b).

Therefore, subsequent discussion of results is divided into two sections, based on scanning direction (i.e. perpendicular and parallel).

All analyses (XRD and NIR) were performed at the Camborne School of Mines (CSM) laboratory, UK.

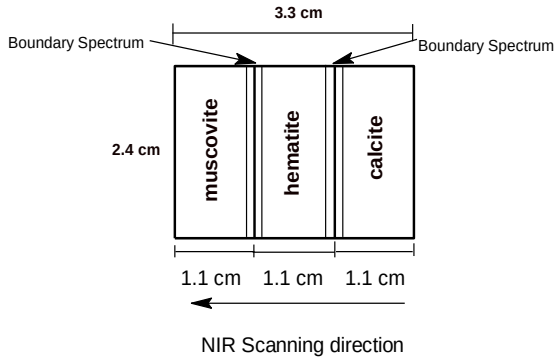

Figure 1. Perpendicular alignment of powdered mixtures

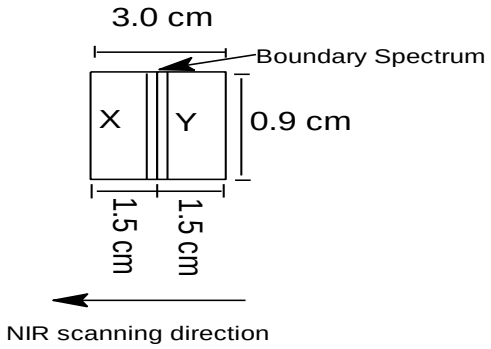

Figure 2. Perpendicular alignment of solid mixtures

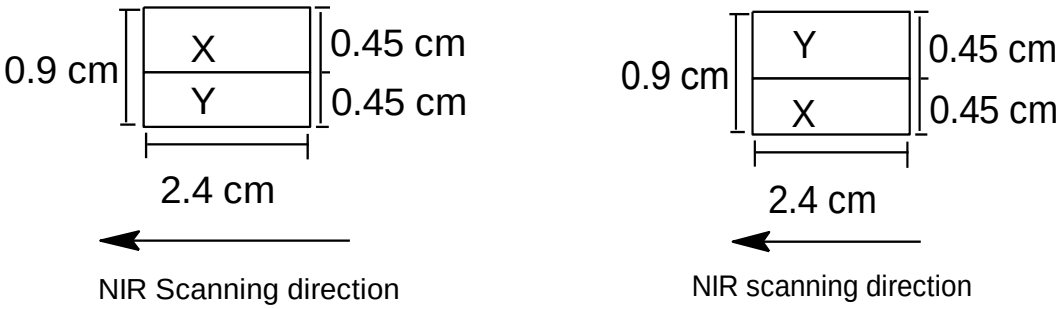

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Figure 3. Parallel alignment of mixture of solid minerals. (A) Normal and (B) Transposed.

3. Discussion of results and implications to ore sorting

3.1. Perpendicular alignment

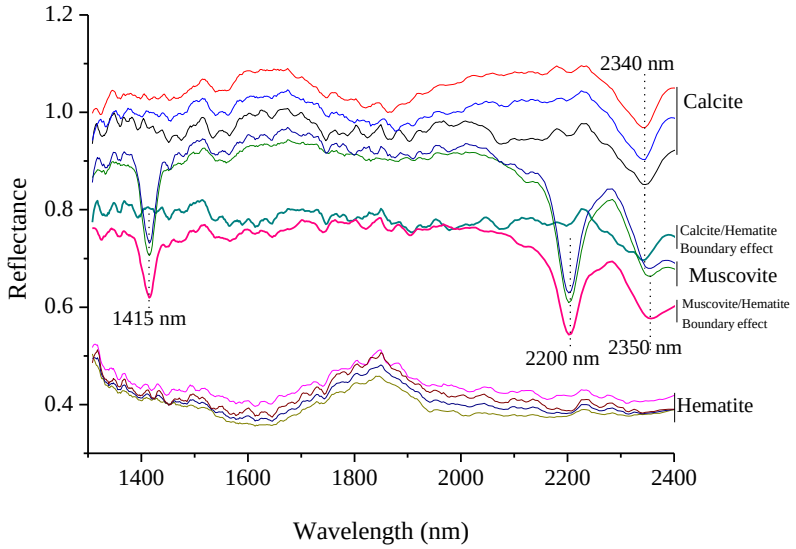

Figure 4. NIR spectra of perpendicular alignment of powdered calcite-muscovite-hematite

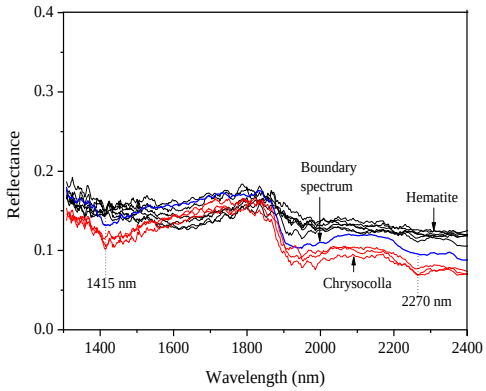

Figure 5. NIR spectra of perpendicular alignment of hematite-chrysocolla

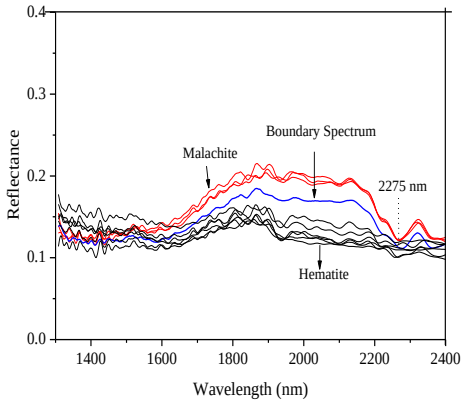

Figure 6. NIR spectra of perpendicular alignment of malachite-hematite

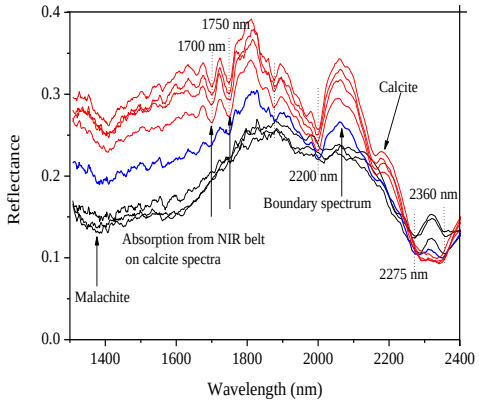

Figure. 7. NIR spectra of perpendicular alignment of calcite-malachite

Given that each NIR spectrum related to a surface area of 2.9 by 9 mm, each mixture produced between 11 and 9 spectra. For the powdered samples (Figure 4), analysis revealed that hematite and calcite produced four spectra each, while three spectra were produced by muscovite. Two spectra, one each of calcite and muscovite were affected as a result of contact with hematite. The affected spectra showed a reduced reflectance or overall brightness relative to other spectra of the same original composition. This phenomenon is here referred to as a boundary effect. The unaffected spectra displayed diagnostic features corresponding to the constituent functional group(s) of each mineral, all appearing with maintained wavelength position(s).The boundary effect was also observed in spectra of solid mixtures that appeared along contact zones (Figures 5, 6 and 7). Hence, though the boundary spectrum can be said to have the composition of both minerals, the absorption features (centres) retained depicts the dominant

mineral. Therefore, mineral discrimination using NIR sensors will be better achieved by selecting absorption features locations of individual constituent minerals rather than their overall reflectance values.

Figure 5 shows a boundary spectrum lacking absorption features. While the overall reflectance differs from that displayed by chrysocolla or hematite the spectrum confirmed the dominance of hematite over chrysocolla along the NIR region[5]. However, in the mixture involving calcite and malachite (Figure 7), the boundary spectrum showed features of both minerals. The features of malachite, though weak, were observed at longer wavelengths (2275 and 2360 nm), while calcite's 2340 nm feature appeared broad lacking a well-defined centre. Calcite showed additional feature near 2000 nm. Consequently, the visibility of only muscovite/calcite and malachite in Figures 4 and 6 is due to the non-feature displaying characteristics of hematite. Hence, it can be concluded that when, two absorption features displaying NIR-active minerals occur alongside one another in vertical association, the resultant contact spectrum will or is likely to display absorption features corresponding to both minerals.

Figure 7 also showed calcite spectra displaying features corresponding to the NIR line scanner belt. The penetration of NIR radiation beyond 0.7 cm reveals that the depth of NIR penetration of a mineral or sample depends on its opacity and can range up to several millimetres. Thus, confirming findings reported by Iyakwari et al. (2013).

Hence, when processing ores consisting of large mineral grains, spectra are likely to display boundary effects. Therefore, further crushing will be required to liberate individual minerals. The degree of liberation will depend on the mineral particle size of the ore and NIR spectrum dimension. Consequently, for classification purposes, if the boundary spectrum reveals features of one mineral relative to the other, classification can be achieved. This is true for mixtures with hematite (Figures 4, 5, and 6), since the absorption features of the other minerals in the boundary spectrum are not visible. The boundary spectrum can be assigned to the minerals showing features or dominance in concentration (i.e. calcite and muscovite (Figure 4), hematite (Figure 5), and malachite (Figure 6) respectively). For mixtures of calcite and malachite (Figure 7), a boundary spectrum only allows identification of the minerals in concentration, since both minerals show their features side-by-side (spectrally mixed). Therefore, classification or discrimination will not be achieved, unless the sample is further crushed to liberate the individual minerals. Where the degree of spectral mixing is high, across all spectra of a particle, liberation may not achieve better resolution, hence NIR may not be applicable for preconcentrating such ores as valuable materials are likely to be lost as waste.

Also, comparison of Figure 4 with Figures 5, 6 and 7 indicated that the powdered sample displayed higher reflectance than the solids. This confirms finding by Clark (1999), who stated that larger particles have a greater internal path where photons may be absorbed. Hence, due to multiple scattering in the NIR region, the powdered samples reflected more light, while the solids absorbed more.

When making decisions relating to mineral identification and/or ore preconcentration, use of wavelengths close to feature(s) associated with the belt should be avoided.

3.2. Parallel alignment

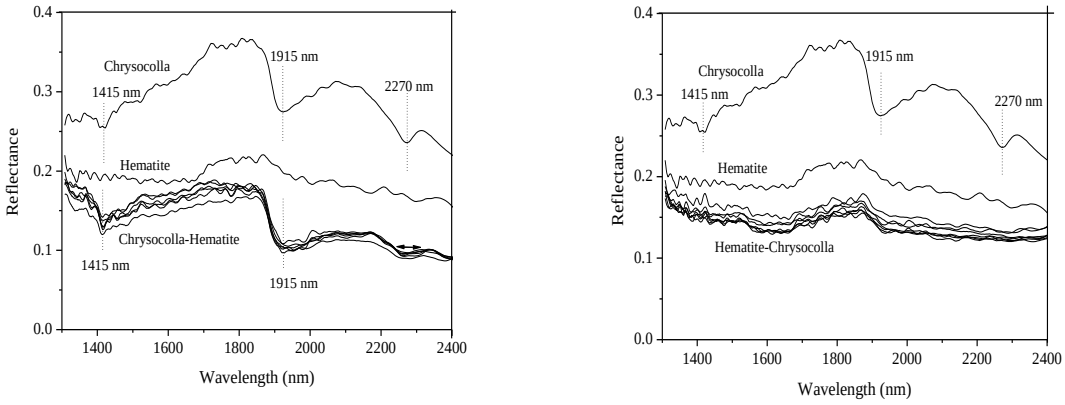

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Figure 8. NIR spectra of chrysocolla and hematite parallel alignment (A) chrysocolla-hematite and (B) hematite-chrysocolla. including reference spectra

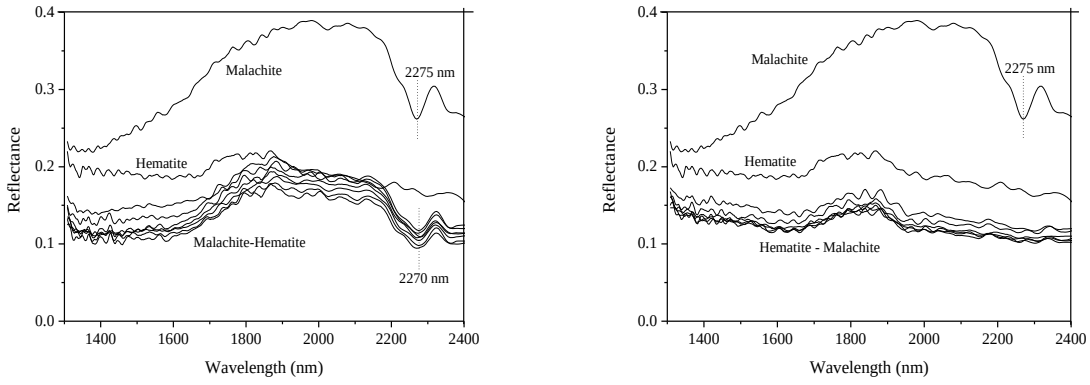

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Figure 9. NIR spectra of Malachite and hematite parallel alignment (A) malachite-hematite and (B) hematite-malachite, including reference spectra

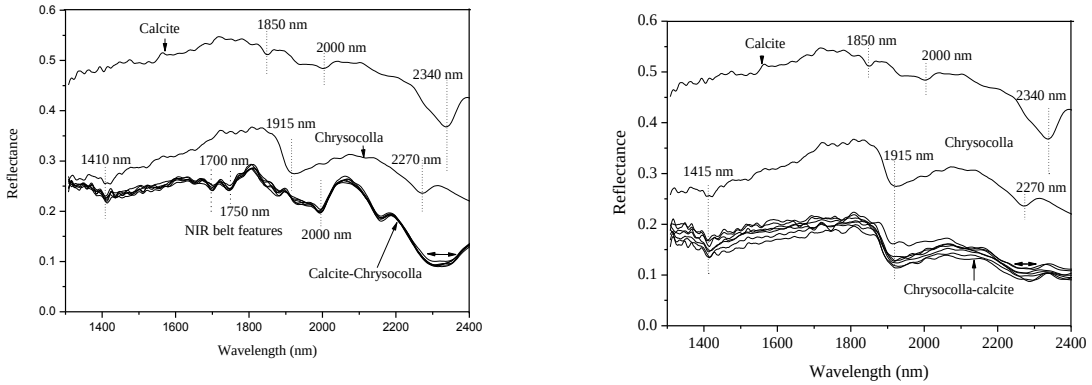

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Figure 10. NIR spectra of chrysocolla and calcite parallel alignment (A) calcite- chrysocolla and (B) chrysocolla-calcite, including reference spectra.

Analysis revealed that for each mixture, spectra dominance was dependent on the constituent minerals. Spectral analysis of mixtures involving chrysocolla (Figures 8 and 10) revealed that the chrysocolla feature near 2270 nm appeared broad and lacking a defined absorption centre. Other chrysocolla features (1415 and 1915 nm) were visible in spectra when chrysocolla was positioned above the other mineral (Figures 8a and 10b). For mixtures involving hematite (Figures 8 and 9), hematite dominated spectra when first encountered by NIR. The same can also be said of malachite, which dominated spectra when first encountered. For mixtures of calcite and chrysocolla where calcite is positioned above chrysocolla, spectra appeared mixed displaying features of both minerals and also revealing features relating to the NIR belt (Figure 10).

With the exception of calcite-chrysocolla mixtures, minerals positioned above the other dominated spectra, with little or no trace of the second mineral's absorption features in the resultant spectra. Therefore, though both minerals appeared along the same spectrum width, the first (top) mineral is more in contact and accessible to the NIR radiation, thereby dominating the spectra, while the mineral underneath it is more or less invisible. Hence, dominance in such situations is position or exposure dependent. With respect to above, the samples although optically separated do not experience boundary effect as was observed in the perpendicularly aligned sample.

4. Conclusion

Establishing the presence of diagnostic features at specific wavelengths positions of individual NIR-active minerals in an ore is essential in scoping efficient NIR application for ore

preconcentration. Depending on the NIR-active minerals in concentration and type of arrangement, spectral dominance may depend on: (a) individual mineral NIR sensitivity and or (b) mineral position (arrangement) or exposure along the line of view of the line scanner. NIR radiation penetration of calcite particle confirmed the depth of NIR penetration to be mineral opacity dependent.

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